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THE ECONOMIC POTENTIAL OF DIFFERENT ADVANCED REACTOR CONCEPTS IN A FUTURE POWER GENERATING SYSTEM

by

A. Boettcher, H. Kraemer, K. Wagemann

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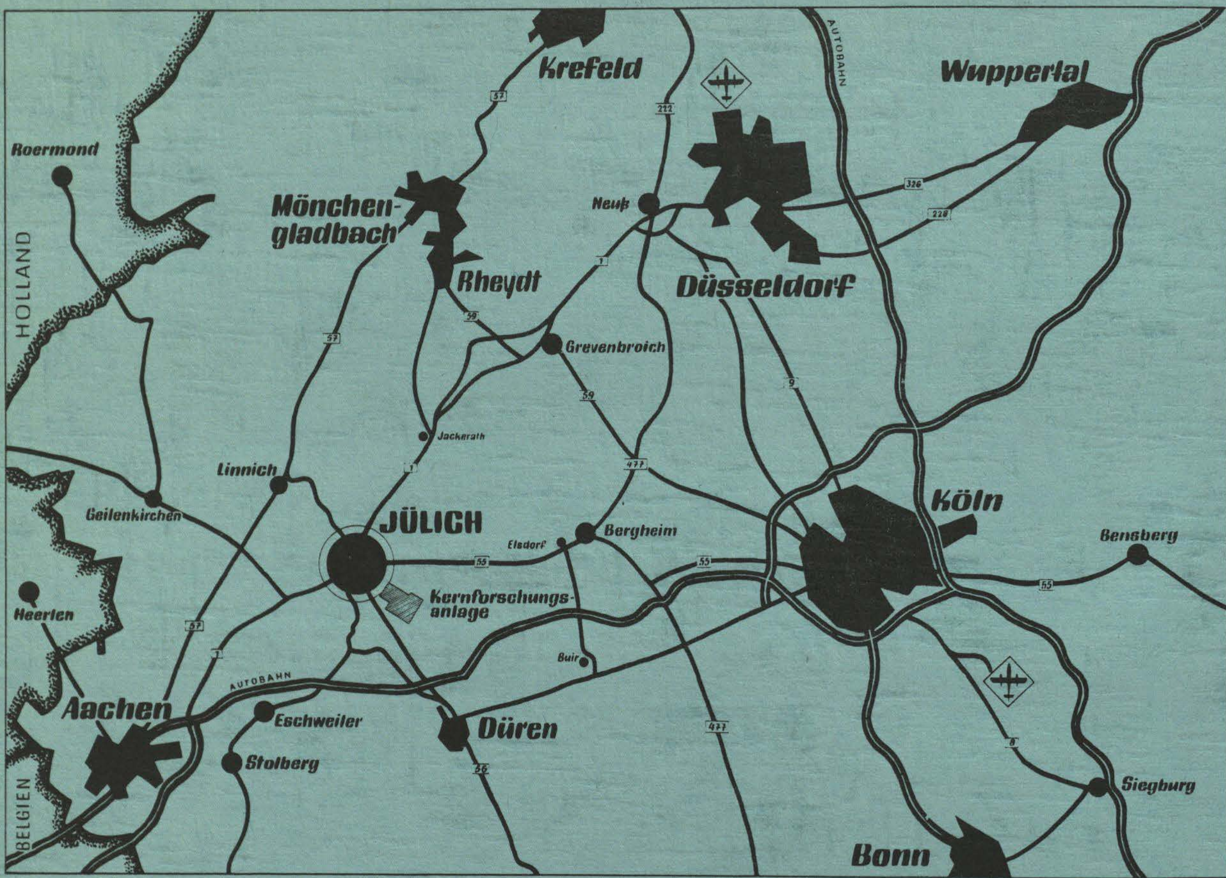

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Power Generating Systems - Economic Potential
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A decisive factor in the evaluation of power reactor lines for large industrial nations is the relative economic potential of the different reactor systems. This is quite apart from more general considerations such as safety, plant availability and the available fuel supply. An isolated study of the single reactor types is not sufficient for such an evaluation because of the mutual interdependendies involved between them. The economics of single reactor types is influenced by the characteristics of the power grid system, especially by the load curve, as well as by differences in economic conditions such as interest rates. However, evaluation studies which are as reliable as possible are needed in order that the optimum combination of different reactor types can be selected for promotion and development. From the large number of reactor systems which have been proposed, those reactor types should be selected which lead to the lowest overall power generating costs when considered together with already existing power stations.

Computer program

The computer program on which this work is based was proposed in its original form by Harde and Memmert[1]. In partly expanded form, it has been employed in several recent investigations[2, 3, 4]. The essential characteristics of this program which form the basis of the following investigation are:

Up to ten different power station types can be added to a power generation system whose total energy requirements with respect to time is known. Power stations are added to the system in such a way as to minimize the overall power generating costs over a time period of a year or longer. For each load range of the specified annual load characteristic curve those plants are chosen which produce the lowest costs. A number of restrictions are imposed here. For example, it must be taken into account that even though the load characteristics of existing power stations vary with time, the plants remain in operation throughout their whole lifetime. The lifetime of a power station is taken to be 25 years in the Federal Republic of Germany and 30 years in the USA. A further restriction is imposed by the rate at which new reactor lines can be added to the system following their initial introduction. The price of uranium is assumed to be a variable which increases as a function of the total cumulative consumption. This function has been selected in such a way that the resulting uranium prices can be regarded as upper limits.

The program requires as input data all essential economic and technical data relating to the construction and operation of the plants. The output of the program consists of: the economically optimal allocation of capacity within the energy generating system for the different type plants considered in the study; the cumulative total power generation costs for arbitrarily specified periods; curves showing the requirements for uranium and uranium separation work as a function of time; the throughput quantities for the main processing plants used in the fuel cycle as well as the average utilization of each type of plant.

Power station lines considered

The only conventional power stations included in the study were those employing fossil fuels. These were combined into one group using averaged data. Converter reactors included in the study are the light water reactors and the gas-cooled high temperature reactors. Light water reactors were included because it is already discernible today that they will attain a large share of nuclear power generation during the coming decade. High temperature gas-cooled reactors with a steam generator or a direct cycle helium turbine have already reached a high state of development and show significant cost advantages over the light water reactor. The importance of various breeder reactors for future power generation appeared to be of special interest. For this reason, three different systems were considered. These are the sodium-cooled fast breeders using either oxide or carbide fuels and the molten salt thermal breeder.

It was assumed that the light water reactors (LWR) can be built on a purely commercial basis after 1970. Commercial availability of the gas-cooled high temperature reactor with a steam turbine (HTR-ST) was assumed by 1975 and the HTR with a helium turbine (HTR-HT) by 1980. The introduction of fast breeders with oxide fuel (NaB-O) was assumed to occur by 1980 and fast breeders with carbide fuel (NaB-C) by 1985. The introduction date of the molten salt breeder reactor (MSBR) to the power grid system was taken to be the same as for the (NaB-O) breeder.

Realistic input data for the various systems are of course essential for the validity of the results. Because of the differing states of development of the various reactor lines, however, the reliability of the data varies. For cases where important data appeared to be particularly unreliable, they were varied within reasonable limits. With the exception of the data assumed for the molten salt breeder *, all data were established on the basis of European conditions. To the extent possible, the data for the different reactor lines were made to be consistent with each other. The fuel cycle costs for the molten salt breeder were taken from publications of the Oak Ridge National Laboratory. It did not seem meaningful to use directly the capital cost estimates quoted in these publications since it is difficult to compare them with European figures. Therefore, the specific capital costs for the molten salt reactor were varied over the whole range of costs of the other systems. In this way, the maximum admissible capital costs for the molten salt breeder reactor could be ascertained if it is to compete favorably with fast breeder systems.

*Data given in ORNL Report No. 3996 for the two zone MSBR were used in these investigations.

The set of data used in this study is listed in Table I.

Results for the power supply grid of the Federal Republic of Germany

The different types of power stations considered in this study were investigated jointly in various combinations in order to establish their specific influences on the future power supply grid of the Federal Republic of Germany. For this reason, the economic and financial conditions which prevail in Germany formed the basis of the study. In order to illustrate the influence which special characteristics of the particular grid system can exert on the optimum capacity distribution, computations were also carried out for the American energy market. The results obtained in this study are shown at the end of this paper. In the following sections, the results obtained for the distribution of the total installed capacity for some of the more important combinations of reactor types are presented. The time range considered in the study is from the years 1970 to 2010.

Figure 1 shows a power system composed of conventional power plants, light water reactors (LWR), and fast sodium-cooled breeders using oxide fuel (NaB-O). In recent years, this system has aroused special interest both in the Federal Republic of Germany and in the USA. It was assumed in this study that no appreciable free plutonium market will exist after 1980 because fast breeders will come into use at about the same time in all western countries. For this reason, the supply of plutonium which will be available to the Federal Republic of Germany is restricted to the amount which has been bred in its own light water reactor system. This severely restricts the introduction of the sodium breeder to the power grid and leads to the light water reactor still being added to the system up to the year 2000. This follows even though this type of plant is economically inferior to the sodium breeder. It is noteworthy that conventional power plants still account for a substantial proportion of capacity after the year 2000. Because their capital costs are lower than those of light water and sodium breeders,the conventional plants serve mainly to help meet peak load requirements. In this range they achieve lower power generation costs than are obtained with the nuclear plants. The cumulative power generation costs of this system are shown in Table 2 as case 1. The economics of the overall system cannot be improved by initially charging the breeders with U-235. The disadvantage of this scheme is the extremely high separation plant capacity which would be needed for a period of some ten years.

Introduction of a gas-cooled high temperature reactor with Thorium cycle into the system leads to considerable shifts in the capacity distribution. Figure 2 shows that the high temperature reactor quickly takes over a high proportion of the added plant capacities following its initial introduction in the year 1975. This comes mainly at the expense of the light water reactors once the initial restrictions to the use of the HTR are eliminated. Here again a closed plutonium market was assumed and the resulting decreased production of this fuel means that fast breeders cannot be added to the system as rapidly as before. As indicated by No. 2 in Table 2, the cumulative cost savings for this case compared to case 1 amount to 1.8 billion Dollars by the year 2010. If sodium-cooled fast breeders with carbide fuel are introduced in 1985 instead of high temperature reactors in 1975, the cost savings are not nearly as great (see Table 2, No. 3). The primary reason for this is the late addition of this advanced reactor type and the shortage of available plutonium. If one assumes that the high temperature reactor employing a direct-cycle helium turbine can be introduced in the year 1980, the savings in cumulative costs are even greater than in the case considered previously (see Table 2, No. 4). Finally, if a molten salt breeder is added to the three basic types in the system instead of the gas-cooled high temperature reactors and the carbide fueled sodium-cooled fast breeder, this reactor takes over, in a similar manner to the high-temperature reactor, a large proportion of the capacity - again at the extense of the light-water reactor mainly.

Table 2, No. 5, shows the upper and lower limits of these costs as a function of the specific capital costs. For the lower limit, the same capital costs as those for light water reactors were assumed and the upper limit uses the capital costs of the sodium-cooled fast breeder. Adding the advanced sodium-cooled breeder reactor with carbide fuel to the system causes the costs to fall even more. This is shown by Table 2, No. 6. Here and in all following cases with the exception of case 5 a, capital costs of 135 $ /kWe were assumed for the molten salt breeder reactor (MSBR). Figure 3 shows the allocation of the total capacity to the different reactor types for this system. The MSBR, which uses U-235 as startup fuel for a long period of time, is very successful on the basis of the capital costs used in the calculation.

If high temperature reactors with steam or helium turbines are added to the system instead of the advanced fast breeder with carbide fuel, the cumulative costs again fall considerably. This is shown by Table 2, No. 7, where the costs nearly reach a minimum for the cases considered. Figure 4 illustrates the allocation of the capacity to the different reactor types for this system. It can be seen that for the case in which the capital costs of the MSBR are taken to be the same as for the HTR-ST, the molten salt breeder reactor achieves roughly the same level as the high temperature reactor with a helium turbine.

If the MSBR in the system is replaced by the fast breeder with carbide fuel (Table 2, No. 8), the cumulative costs reach only slightly lower levels than when the NaB-C is left out. This is because of the late introduction date of the advanced fast breeder and the fact that a closed plutonium market is assumed. Finally, if one considers a system which includes gas-cooled high temperature reactors with helium turbines, molten salt breeders and fast breeders with carbide fuel, the resulting cumulative costs are very similar to those obtained when the carbide fast breeder is not included. This is seen by comparing the results given in Table 2, No. 9 with the results obtained for case No. 7.

Figure 5 shows the distribution of the total capacity between the different reactor types. For the purpose of simplification, the high temperature reactors with steam and helium turbines have been grouped together as have also the fast breeders using oxide and carbide fuels. This picture changes relatively little if one assumes an open plutonium market as can be seen in Figure 5 a.

Separation plant requirements

In evaluating the different systems, it is of interest to determine the amount of separation work which is required. Figure 6 gives a summary of some of the important cases considered.

The numbers of the various curves correspond to the case numbers given in Table 2. Case 3, which represents a system composed of conventional plants, light water reactors and sodium-cooled breeders with oxide fuel, is seen to have a separation work requirement that ranges about the mean value of the cases considered. This system exhibited the most unfavorable power generation costs of all the cases investigated. When the two different types of gas-cooled high temperature reactors are admitted to this basic three-plant system (case 4), the amount of separation work needed rises sharply. This is because the reduced application of light water reactors greatly suppresses the addition of fast breeders to the system. Case 7 shows that adding the molten salt breeder to the system causes the separation requirements to rise even more sharply at the beginning. This is because the economically less attractive fast breeder is not added to the system as rapidly as would be possible by virtue of the plutonium produced. Later on the demand for separative work will be reduced by the breeding potential of the MSBR. If the molten salt reactor in case 7 is replaced by a sodium-cooled fast breeder with carbide fuel, the amount of separation work needed falls distinctly. This is illustrated by case 8 and occurs because of the higher breeding potential of this reactor type. Finally, if all advanced reactor types are admitted to the system, the amount of separation work required reaches a minimum. This is shown by case 9 where it is seen that the separation requirements after the year 2000 are lowest once the breeding potentials become fully effective.

Estimates for the power supply grid in the USA

The calculations for the US power supply grid are based on energy requirement estimates by Harms [5]. The curve used exhibits a distinctively lower growth rate over its whole range than the corresponding curve for the Federal Republic of Germany. This is particularly pronounced towards the end of this century. Since accurate information was not available concerning the US annual load characteristic curve, the corresponding curve for the Federal Republic of Germany was used in the study. Simularly, the fuel costs for conventional power plants are based on German experience. It is unlikely that the errors introduced by these assumptions qualitatively affect the results obtained. The current interest and tax rates applying to private ownership in the USA, 6 % and 4.2 % respectively, were used. The period of amortization and life of the power plant are both 30 years. For an insurance rate of 0.2 % this leads to an annuity of 11.9 %.

The situation in the USA differs qualitatively from that in the Federal Republic of Germany because the light water reactor in America has nearly a five year head start. The other reactor concepts will be commercially developed at about the same time in the two countries. Consequently, after 1980 there will be substantially more plutonium available in the USA than in Germany for starting fast breeders. As is shown by Figure 7, the fast breeder can be added at a very much faster rate to a basic three plant system made up of conventional plants, light water reactors and sodium-cooled fast breeders with oxide fuel. The reason for this is the larger quantity of plutonium produced in light water reactors. Corresponding to the faster growth rate of sodium-cooled fast breeders in the USA, the number of light water reactors falls

off more sharply after the year 2000.
The relative potential of the HTR in the power grids of both countries is similar. The gas-cooled high temperature reactor can also prevent the further construction of light water reactors in the USA during the mid-eighties, with the corresponding consequences for the production of plutonium. However, the share of the total capacity for sodium-cooled fast breeders remains higher than is the case for the Federal Republic of Germany. This is because of the higher proportion of light water reactors present at the beginning. (See Figure 8)
Cumulative costs for the two systems up to the year 2010 are listed in Table 2 under headings 1 a and 2 a. These costs have been discounted to the year 1970. Table 2 also shows the annual power generation costs for the two systems. The savings gained by the introduction of the gas-cooled high temperature reactors are considerable.

If the molten salt breeder (MSBR) is admitted to the system in 1980 as the fourth plant type instead of the HTR, the costs are further reduced as compared with case 2 a. The molten salt breeder largely displaces the sodium-cooled fast breeder with oxide fuel, even though its specific capital costs, as assumed in this case, are just as high as those for the fast breeder.

Figure 9 shows the distribution of capacities for a system including all the reactor concepts studied here. Further con struction of the light water reactor line practically ceases in the mid-eigthies. This is due to the influence of the HTR, initially with steam turbines and subsequently with helium turbines. The capacity of the light water reactor line remains relatively constant from about 1990 to the end of the century. During this period, the HTR which at first covered the entire load range is displaced from the base load range. More and more it is used to generate power to meet the medium and peak load requirements. After the year 2000, the capacity of the HTR line continues to rise to meet the increasing demands in this load range.

Based on the capital costs of 135 $ /kWe assumed for the molten salt breeder reactor, this reactor concept is economically superior to the sodium breeder both with carbide and oxide fuels. However, because insufficient quantities of U-233 are initially available for the MSBR, the sodium-cooled breeder is also added to a great extent during this period. After the year 2000, the capacity curve for the sodium breeder levels off to the extent that the demand for U-233 can be satisfied.
The overall power generation costs given in Table 2 under heading 9 a also reach an absolute minimum for the case of the US power supply grid.

The separation requirements for the various systems are depicted in Figure 10. Here, too, a minimum is reached by combining all of the advanced reactor types. The strongly pronounced relative maximum which occurs in all cases in the late eighties is primarily due to the large addition of light water reactor capacity.

Conclusions

Taken as a whole, the investigations show that substantial savings are possible in both power supply grids by the introduction of gas-cooled high temperature reactors.
These savings can be increased by adding sodium-cooled fast breeders with carbide fuel or molten salt breeder reactors. A stipulation for the MSBR is that the specific capital costs must lie between those for fast breeders and light water reactors. The sodium-cooled fast breeder reactor with oxide fuel cannot compete favorably with either the high temperature reactors with helium turbines or with the molten salt breeders. Separation requirements attain a distinct minimum when the three most favorable reactor lines are employed simultaneously. Their simultaneous development appears to be justified by the results of these investigations.

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3	A. Boettcher, H. Kraemer and K. Wagemann:	atomwirtschaft 13, No. 5, p. 249 (May 1968)
4	A. Boettcher, H. Kraemer and K. Wagemann:	atomwirtschaft 13, No. 10, p. 501 (October 1968)
5	V. L. Harms:	"Economic considerations bearing on civil power development", Supplement to "Study made for the ad-hoc-Committee on Atomic Policy of the AIF", Febr. 1962

Table 1: Specific input parameters for the regarded power plants

		Conv. Pl.	LWR	HTR(ST) Recycler		HTR(HT) Recycler		NaB-O	NaB-C	MSBR	
Direct plant costs	\$/kWe	82	91	99		90		105	105	91 - 105	
present worth of the plant when starting operation	\$ /kWe	117,5	117,5	135		125		145	145	127,5-145	
commercial start			1970	1975		1980		1980	1985	1985	
operation costs	\$/kWe.y	1,825	1,825	1,825		1,825		1,825	1,825	1,825	
thermal efficiency	%	38	33	42		48		42	42	45	
ZONE				Breed	Feed	Breed	Feed			Core	Blanket
Relative zone power				0,73	0,27	0,73	0,27			0,996	0,04
fissile material in fresh fuel	%		3,1	2,77	93,15	2,77	93,15	4,8	3,97	100	-
fissile material in spent fuel	%		0,85	3,02	-	3,02	-	6,19	5,37	100	0,00105
mean burnup	MWth d/t		31000	61000	643000	61000	643000	31000	26680	109500	3,88
fuel rating	MWth/t		33,0	65,4	1502	65,4	1502	42	52,9	3260	0,0882
fuel fabrication costs	\$/kg		70	43	750	43	750	100	8,0	112,5	-
fuel reprocessing costs	\$/kg		35	40	-	40	-	64	40	220$^{+)}$	0,9$^{+)}$

$^{+)}$Salt replacement

Table 2: Annual costs of power production (a) and cumulative expenditures (actualized to 1970) (b) for different power generating systems in 10^9 $

		SYSTEM	1980 a	1980 b	1990 a	1990 b	2000 a	2000 b	2010 a	2010 b
BRD	1	Conv. Pl., LWR, NaB-O	2,9	16,7	4,1	28,6	6,5	38,1	9,3	45,3
	2	Conv. Pl., LWR, NaB-O, HTR(ST)	2,8	16,6	3,8	28,0	6,0	36,8	8,8	43,5
	3	Conv. Pl., LWR, NaB-O, NaB-C	2,9	16,7	4,1	28,6	6,2	37,9	8,2	44,6
	4	Conv. Pl., LWR, NaB-O, HTR(ST), HTR(HT)	2,8	16,6	3,8	27,8	5,7	36,3	8,3	42,7
	5	Conv. Pl., LWR, NaB-O, MSBR	2,9	16,7	3,9	28,5	5,7	37,0	8,0	43,2-44,0
	6	Conv. Pl., LWR, NaB-O, NaB-C, MSBR	2,9	16,7	3,9	28,3	5,6	36,8	8,0	43,0
	7	Conv. Pl., LWR, NaB-O, HTR(ST), HTR(HT), MSBR	2,8	16,6	3,6	27,6	5,5	35,7	7,8	41,8
	8	Conv. Pl., LWR, NaB-O, NaB-C, HTR(ST), HTR(HT)	2,8	16,6	3,8	27,9	5,8	36,3	8,2	42,6
	9	Conv. Pl., LWR, NaB-O, NaB-C, HTR(ST), HTR(HT), MSBR	2,8	16,6	3,6	27,7	5,4	35,7	7,7	41,7
USA	1a	Conv. Pl., LWR, NaB-O	19,2	126,5	29,3	222,1	41,3	303,3	55,0	364,6
	2a	Conv. Pl., LWR, NaB-O, HTR(ST)	19,1	126,2	27,9	219,8	39,7	296,8	53,1	356,1
	5a	Conv. Pl., LWR, NaB-O, MSBR	19,2	126,5	28,7	221,4	38,1	298,1	49,3	353,9
	9a	Conv. Pl., LWR, NaB-O, NaB-C, HTR(ST), HTR(HT), MSBR	19,1	126,2	26,6	218,0	36,4	289,6	48,1	343,6

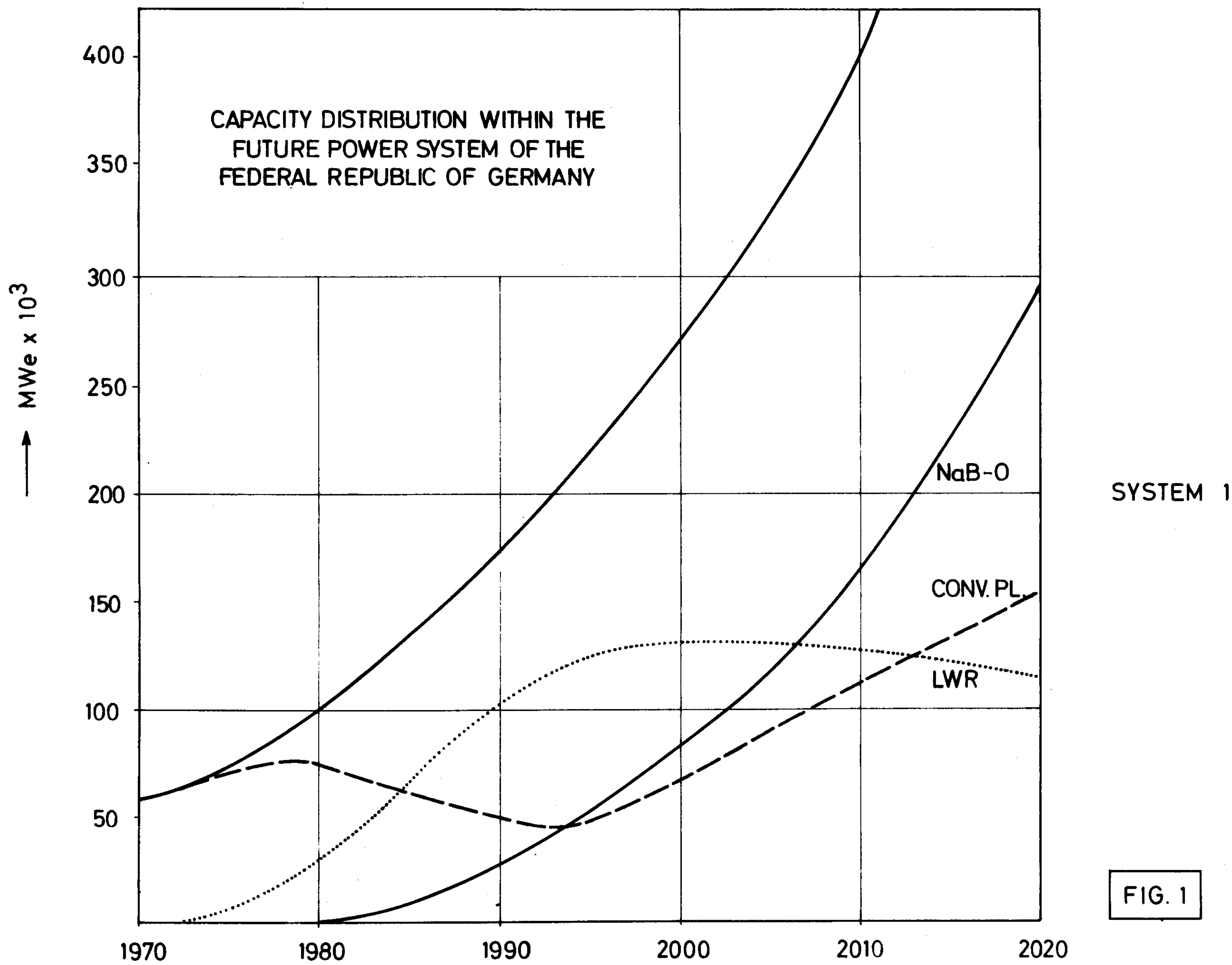

CAPACITY DISTRIBUTION WITHIN THE
FUTURE POWER SYSTEM OF THE
FEDERAL REPUBLIC OF GERMANY
400
350
300
250
200
150
100
50
→ MWe x 10^3
NaB-O
CONV. PL.
LWR
1970
1980
1990
2000
2010
2020
SYSTEM 1

FIG. 1

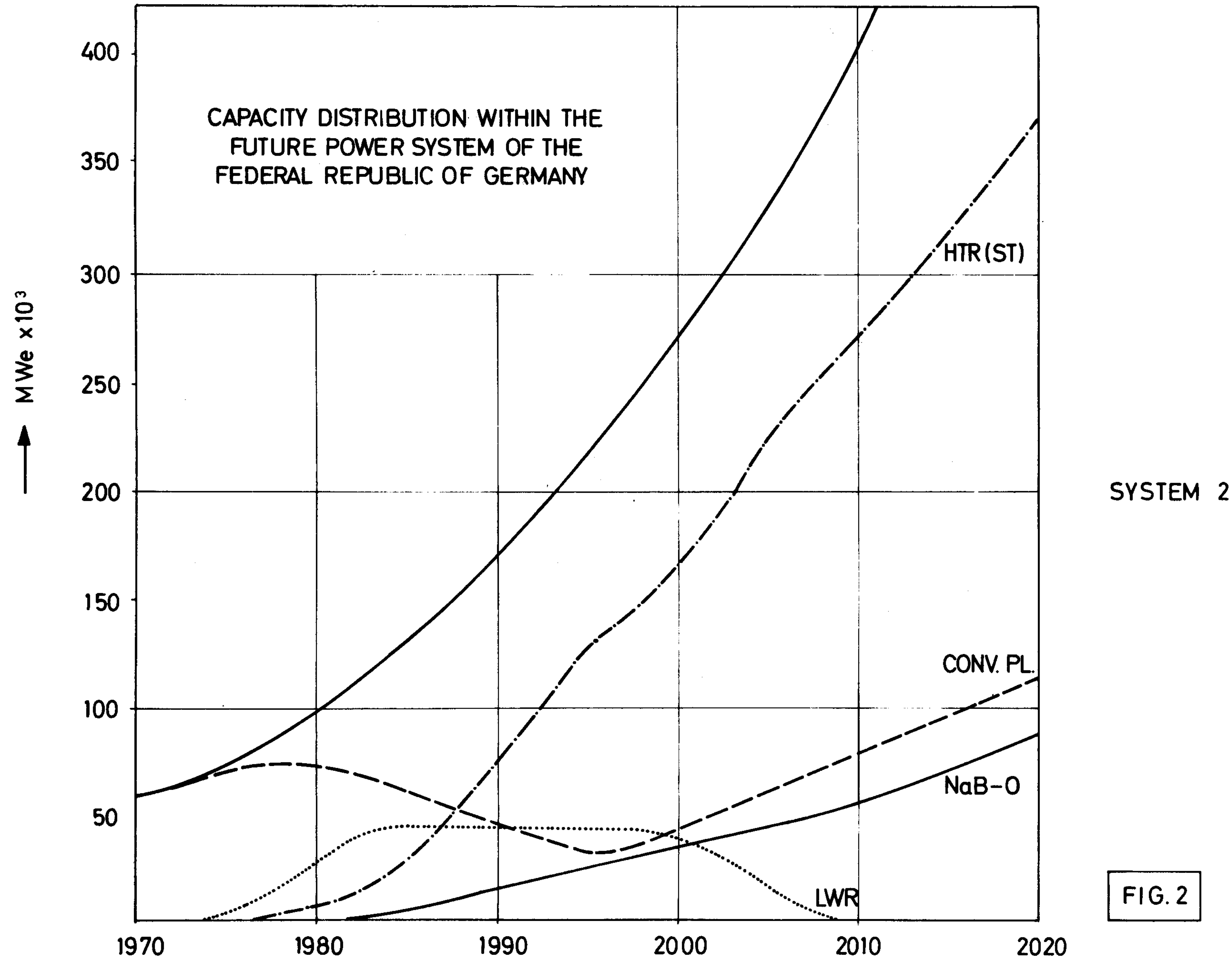
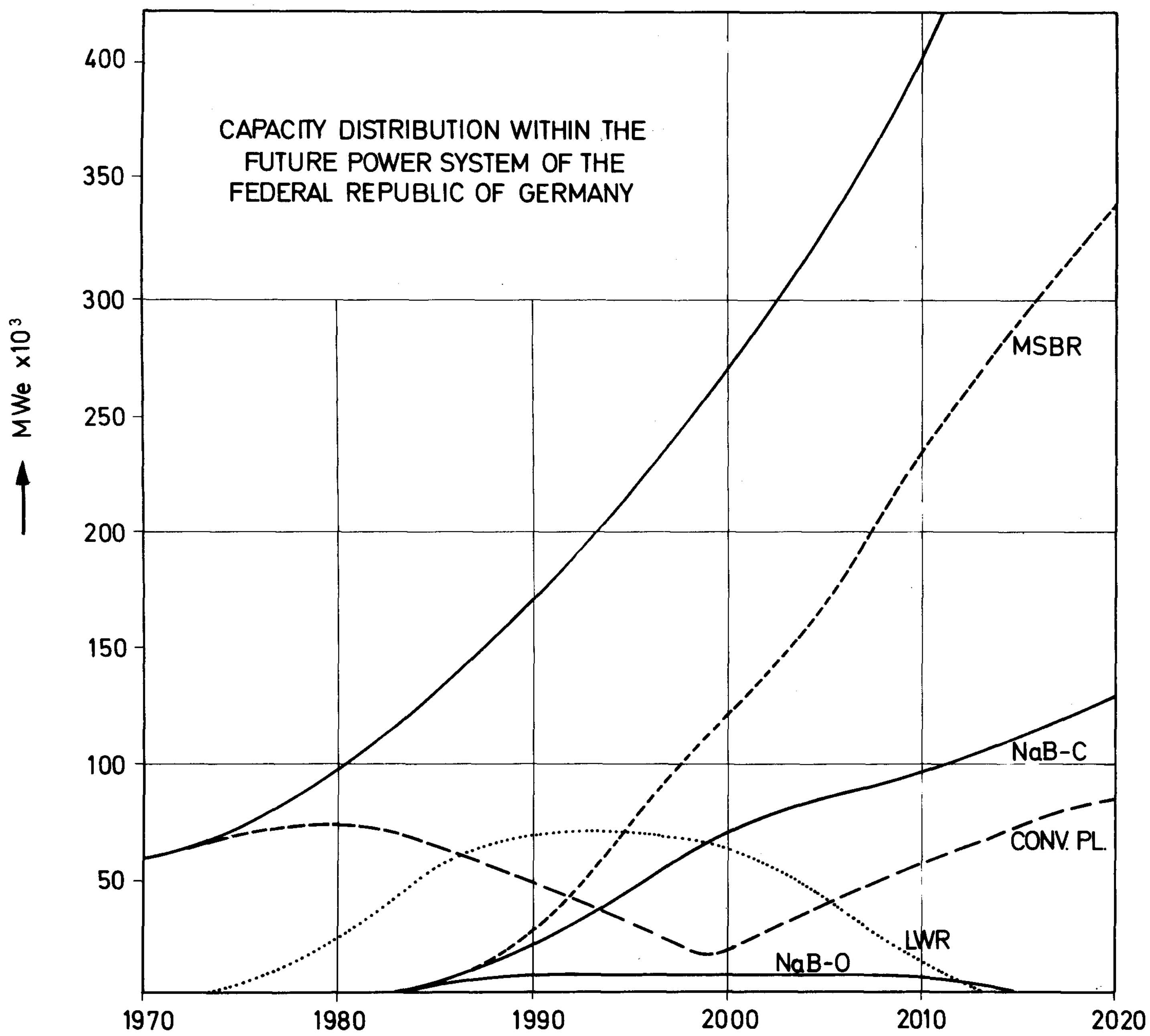
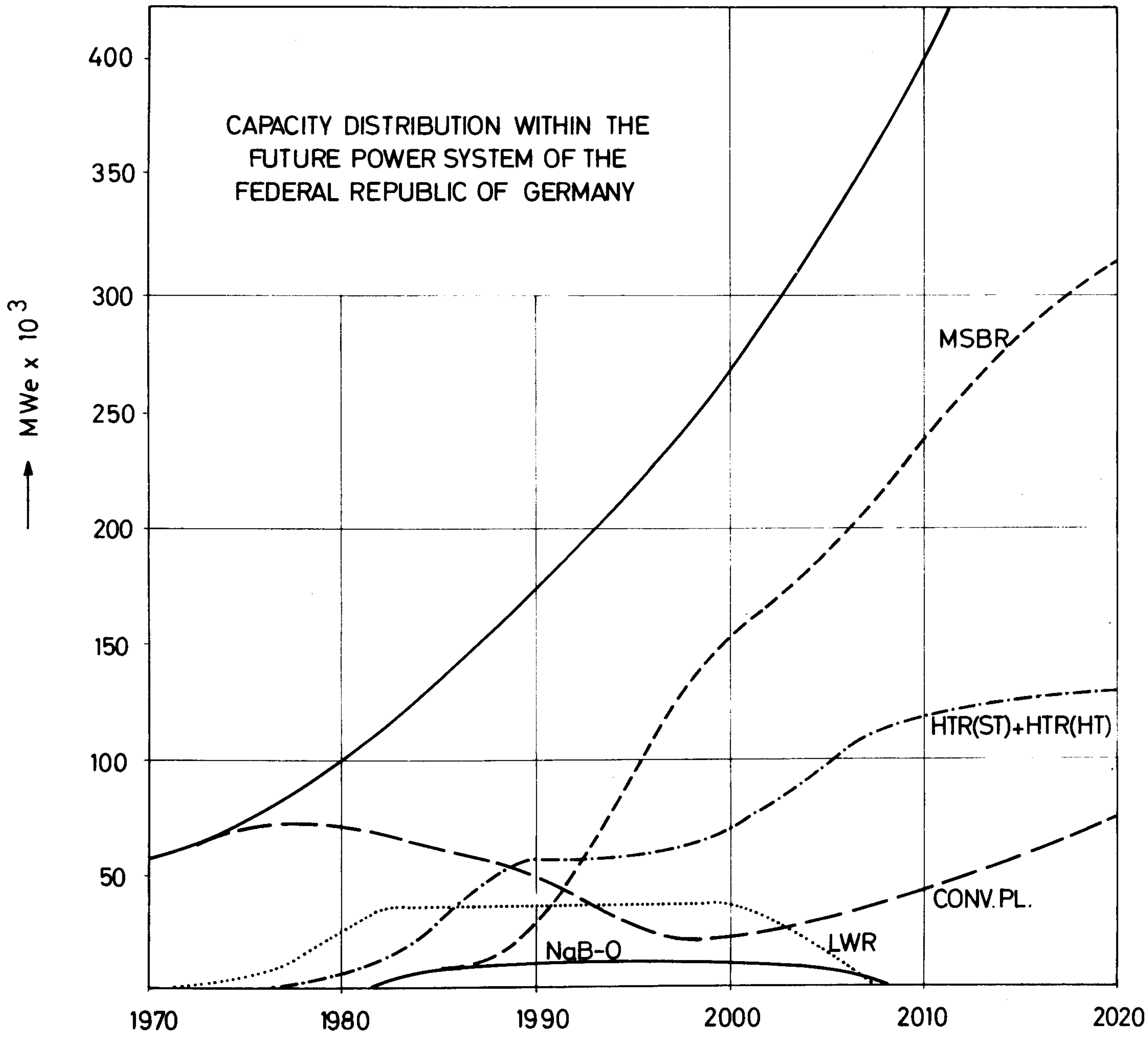

CAPACITY DISTRIBUTION WITHIN THE FUTURE POWER SYSTEM OF THE FEDERAL REPUBLIC OF GERMANY
MWe ×10³
400
350
300
250
200
150
100
50
1970
1980
1990
2000
2010
2020
HTR (ST)
CONV. PL.
NaB-O
LWR
SYSTEM 2

FIG. 2



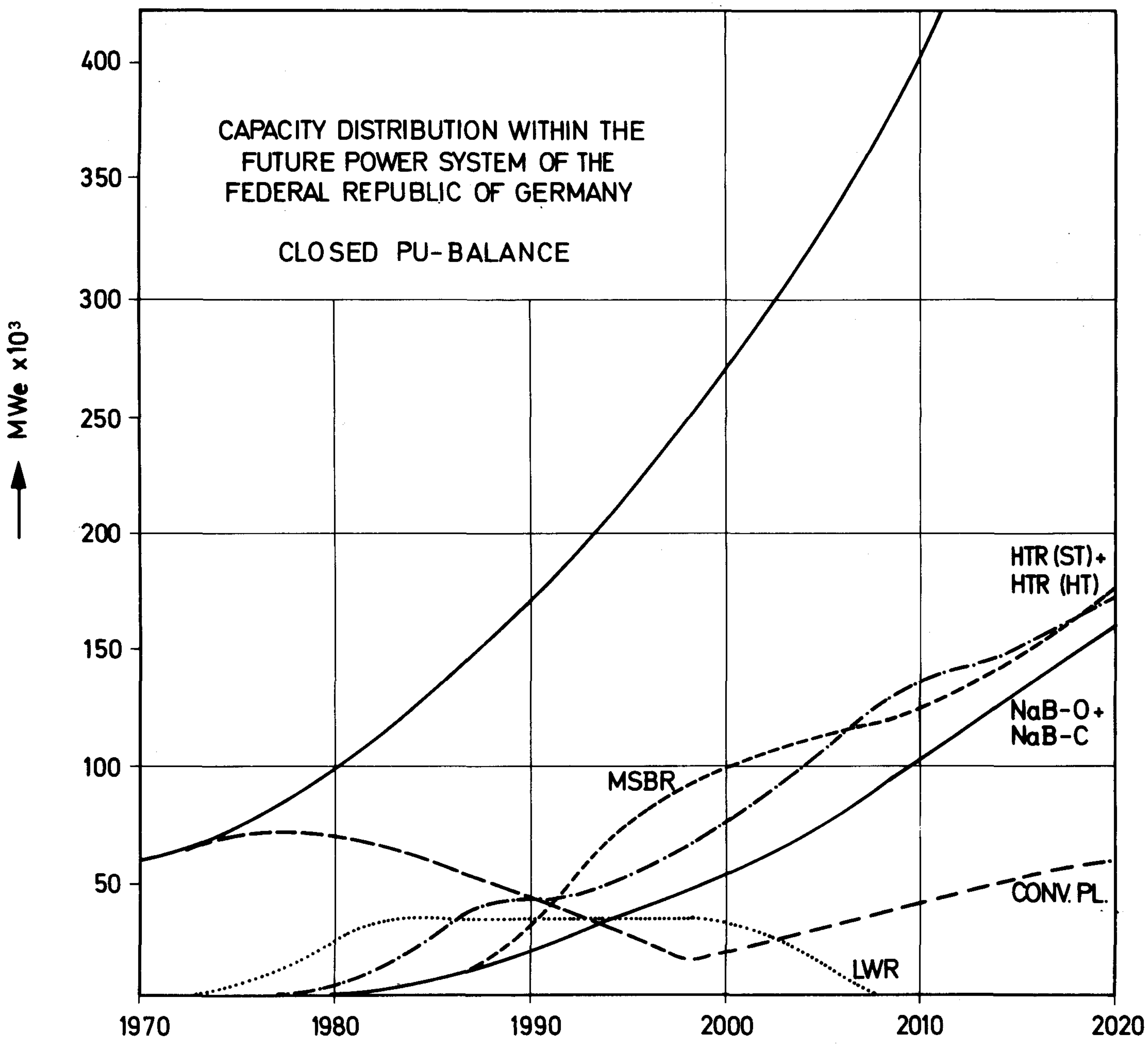
SYSTEM 6

FIG. 3



SYSTEM 7

FIG.4



SYSTEM 9

FIG. 5

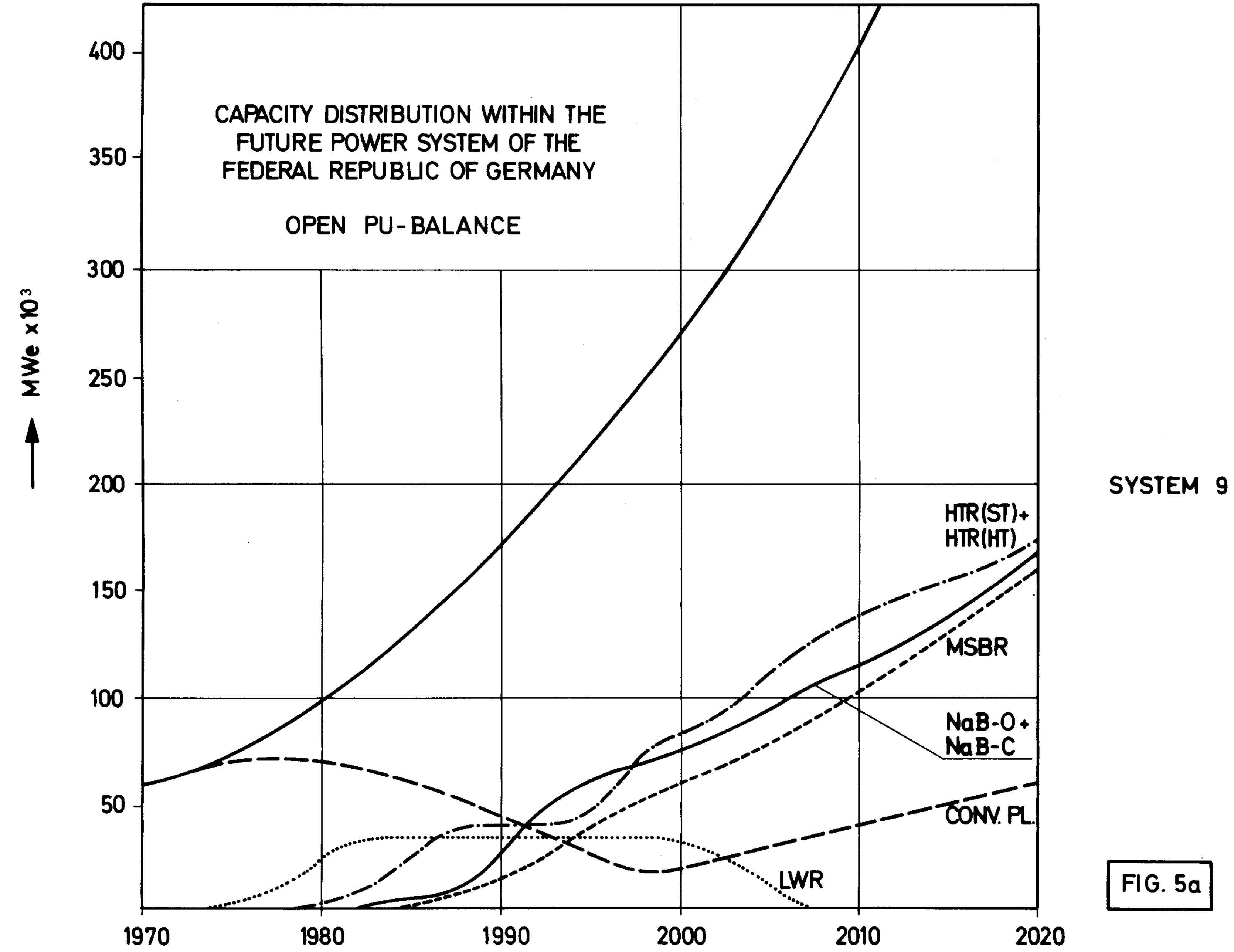

CAPACITY DISTRIBUTION WITHIN THE
FUTURE POWER SYSTEM OF THE
FEDERAL REPUBLIC OF GERMANY
OPEN PU-BALANCE
MWe x10³
400
350
300
250
200
150
100
50
1970
1980
1990
2000
2010
2020
HTR(ST)+
HTR(HT)
MSBR
NaB-O+
NaB-C
CONV. PL.
LWR
SYSTEM 9

FIG. 5a

SEPARATIVE WORK NEEDED FOR THE FEDERAL REPUBLIC OF GERMANY

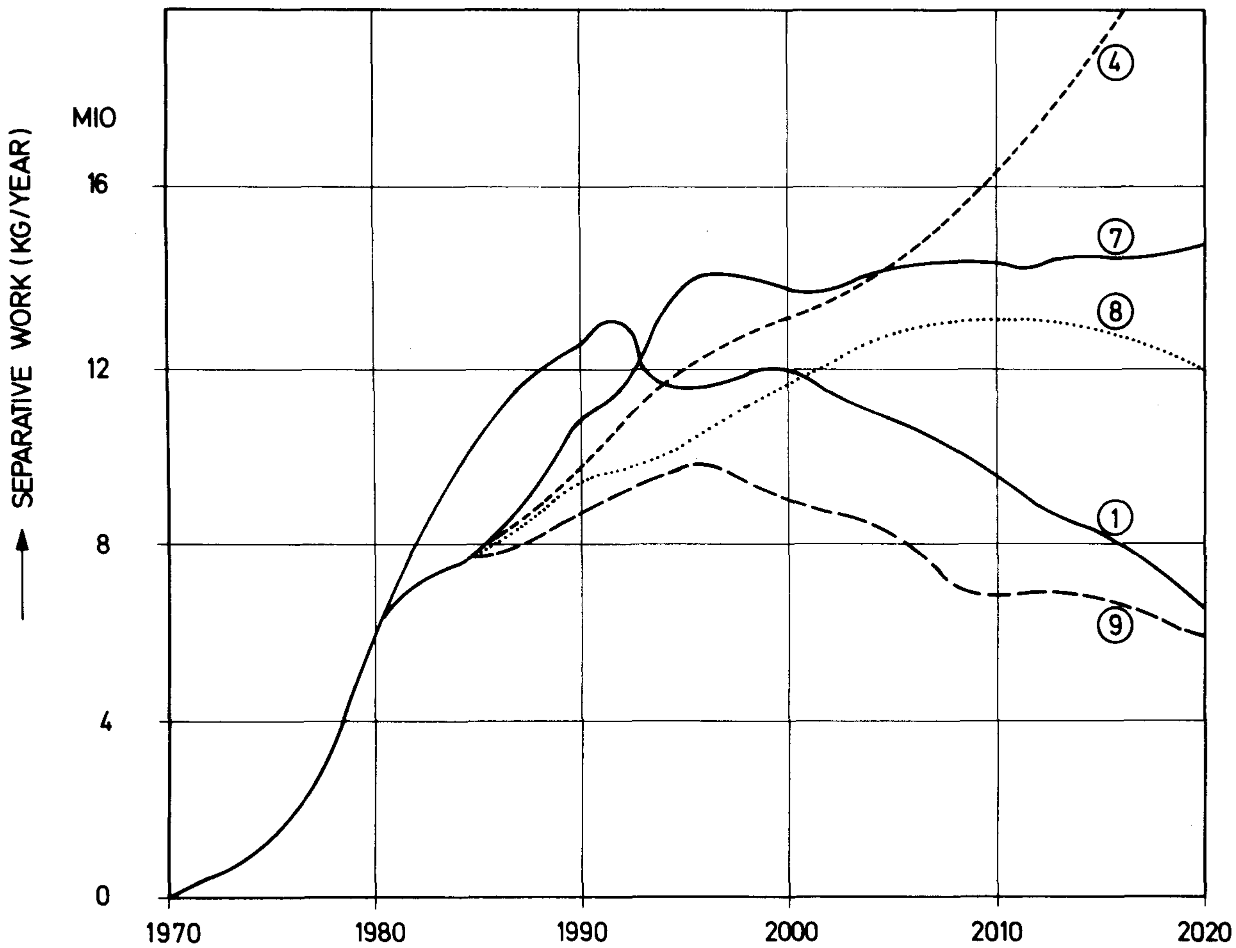
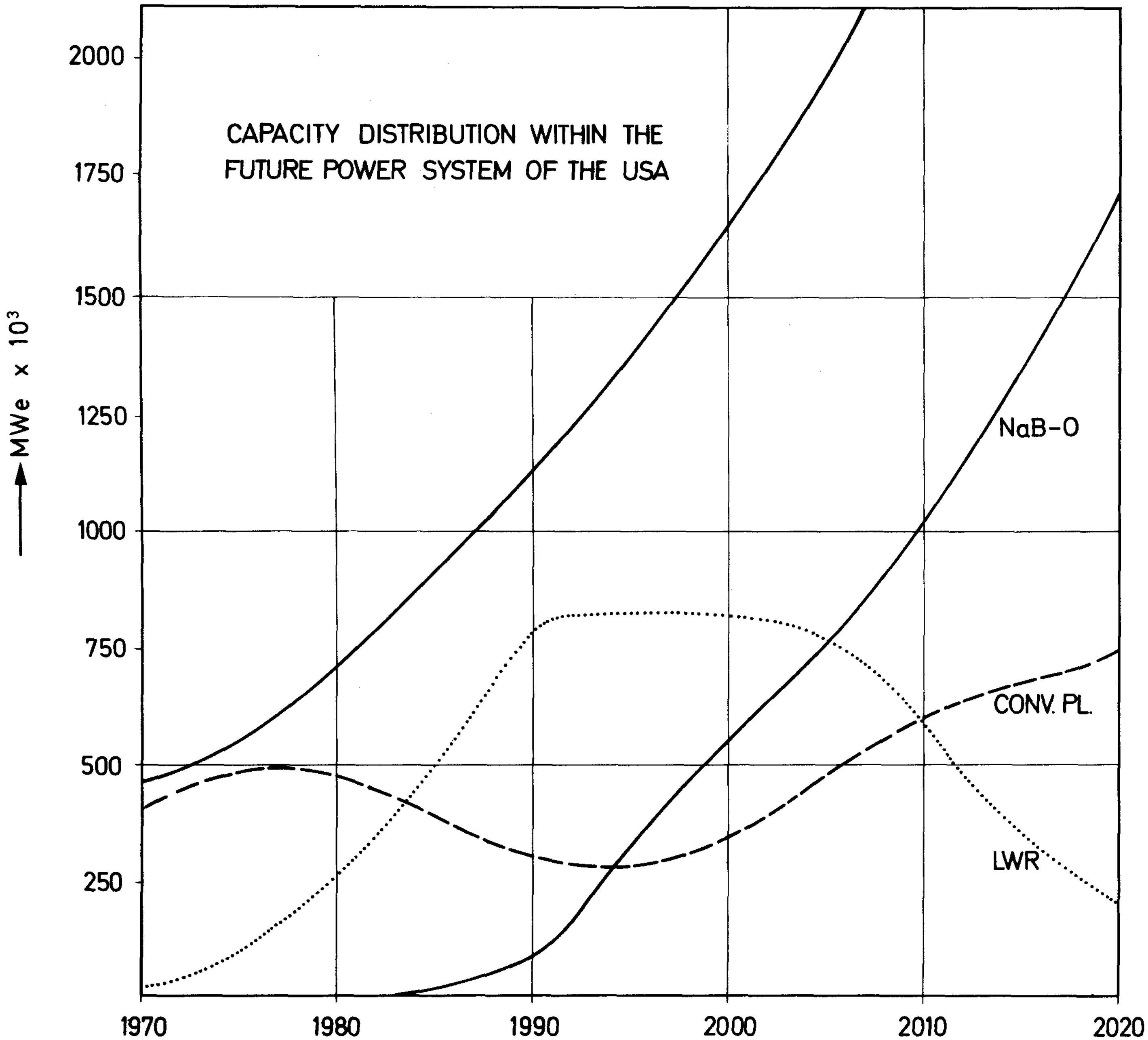


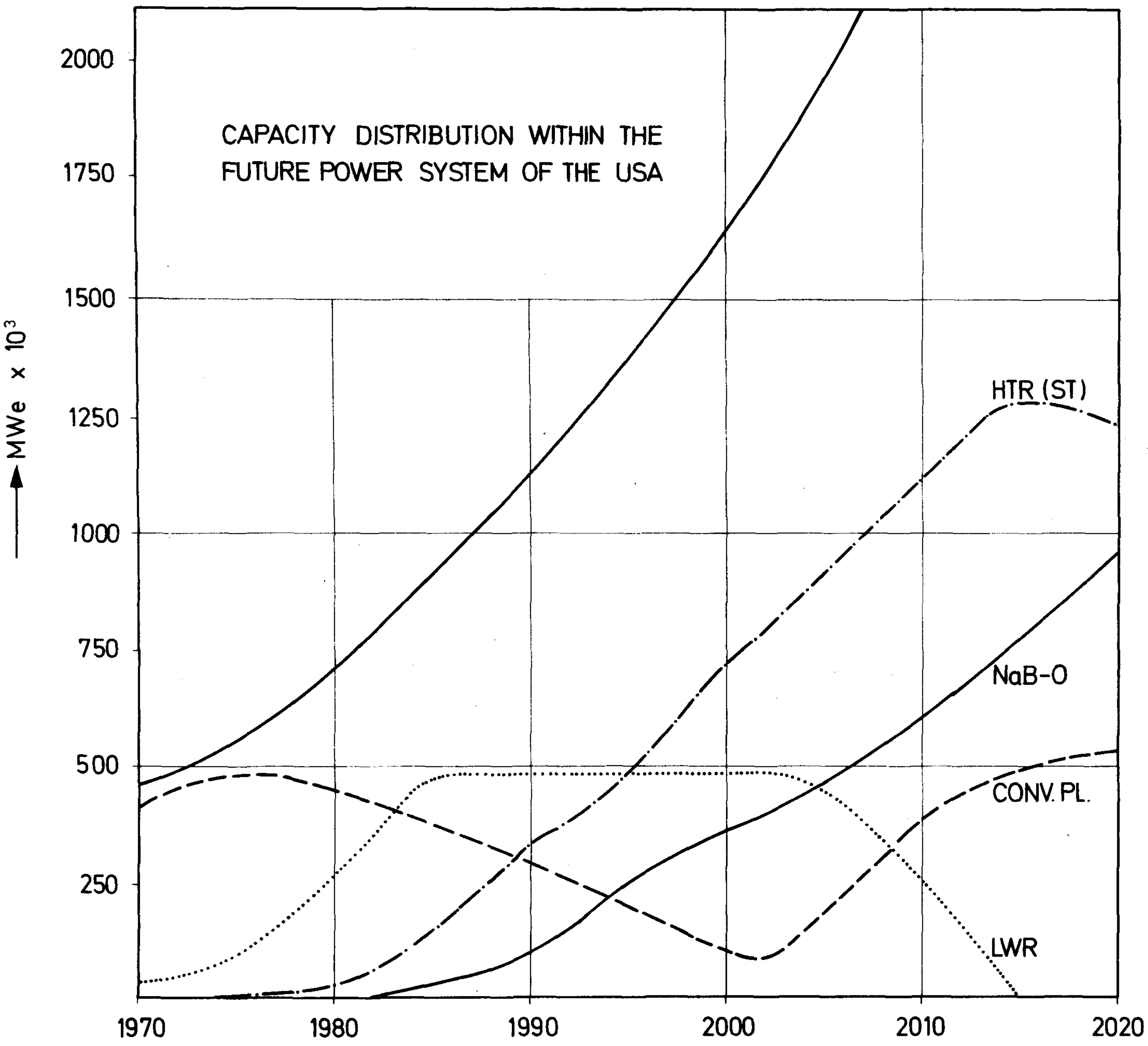
FIG. 6

1	Conv. Pl., LWR, NaB-O
4	Conv. Pl., LWR, NaB-O, HTR(ST), HTR(HT)
7	Conv. Pl., LWR, NaB-O, HTR(ST), HTR(HT), MSBR
8	Conv. Pl., LWR, NaB-O, NaB-C, HTR(ST), HTR(HT)
9	Conv. Pl., LWR, NaB-O, NaB-C, HTR(ST), HTR(HT), MSBR



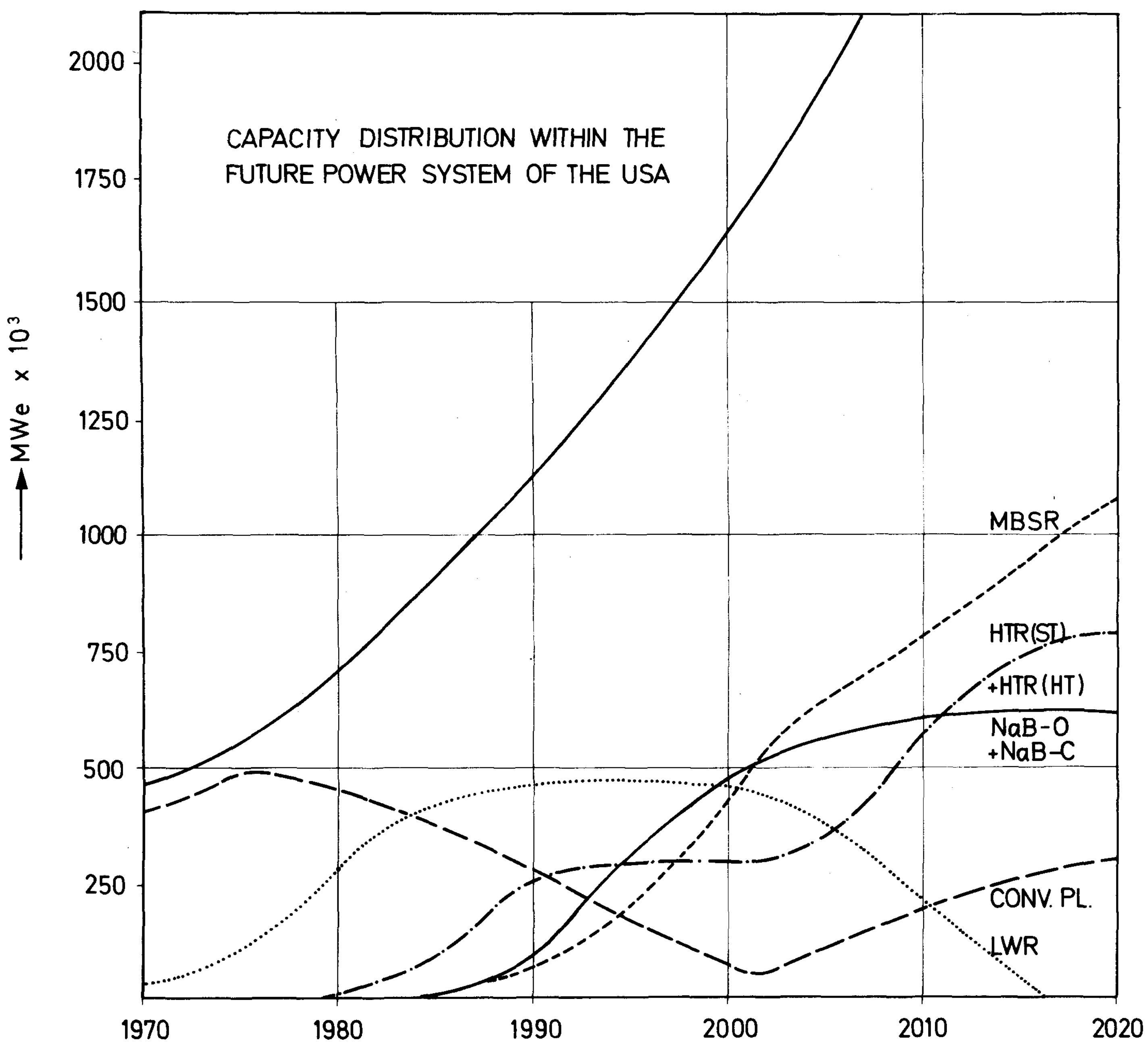
SYSTEM 1a

FIG. 7



SYSTEM 2a

FIG. 8



SYSTEM 9a

FIG. 9

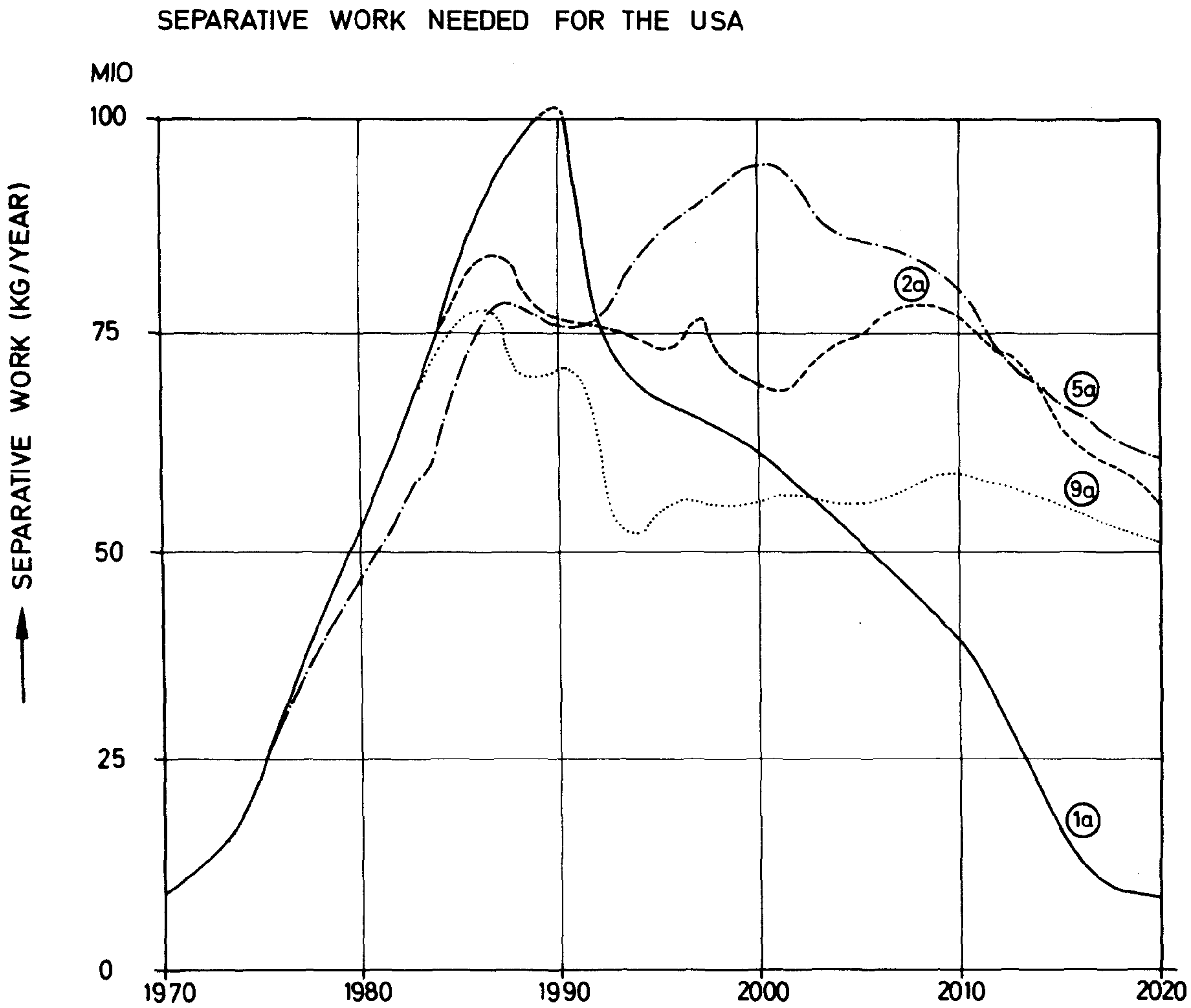


FIG. 10

1 a Conv. Pl., LWR, NaB-O
2a Conv. Pl., LWR, NaB-O, HTR(ST)
5a Conv. Pl., LWR, NaB-O, MSBR
9a Conv. Pl., LWR, NaB-O, NaB-C, HTR(ST), HTR(HT), MSBR